Atmospheric effects on Radar and Communications Operating in Millimeter and Sub-millimeter wavelengths

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1. Introduction

The growing demand for broadband wireless communication links and the deficiency of wide frequency bands within the conventional spectrum, require utilization of higher microwave and millimeter-wave spectrum at the Extremely High Frequencies (EHF) above 30GHz (see table 1).

Table 1: The electromagnetic spectrum.

BAND		IEEE	FREQUENCY	WAVELENGTH
Extremely Low Frequency	ELF		3 - 30Hz	
Super Low Frequency	SLF		30 - 300Hz	
Ultra Low Frequency	ULF		300 - 3,000 Hz	1,000 - 100 Km
Very Low Frequency	VLF		3 - 30 KHz	100 – 10 Km
Low Frequency	LF		30 - 300 KHz	10 - 1 Km
Medium Frequency	MF		300 - 3,000 KHz	1 - 0.1 Km
High Frequency	HF		3 - 30 MHz	100 - 10 m
Very High Frequency	VHF		30 - 300 MHz	10 – 1 m
Ultra High Frequency	UHF		300 - 3,000 MHz	1 - 0.1 m
		L	1 - 2 GHz	
		S	2 - 4 GHz	
Super High Frequency	SHF		3 - 30 GHz	10 - 1 cm
		C	4 - 8 GHz	
		X	8 - 12 GHz	
		Ku	12 - 18 GHz	
		K	18 - 26.5 GHz	
		Ka	26.5 - 40 GHz	
Extremely High Frequency	EHF		30 - 300 GHz	1 - 0.1 cm
		V	40 - 75 GHz	
		W	75 - 110 GHz	
Sub-millimeter (TeraHertz)	FIR		300 - 3,000 GHz	1 – 0.1 mm
Mid infra-red	MIR		3 – 30 THz	100 – 10 µm
Near infra-red	NIR		30 – 300 THz	10 – 1 µm

In addition to the fact that the EHF band (30-300GHz) covers a wide range, which is relatively free of spectrum users, it offers many advantages for wireless communication and RADAR systems as follows:

* Broad bandwidths for high data rate information transfer
* High directivity and spatial resolution
* Low transmission power (due to high antenna gain)
* Low probability of interference/interception (due to narrow antenna beam-widths)
* Small antenna and equipment size
* No multipath fadings (although fading can be caused by atmospheric conditions)

Among the practical advantages of using the EHF region for satellite communications systems is the ability to employ smaller transmitting and receiving antennas. This allows the use of a smaller satellite and a lighter launch vehicle.

Some of the principal challenges in realizing modern wireless communication links at the EHF band are the effects emerging when the electromagnetic radiation propagates through the atmosphere. When millimeter-wave radiation passes through the atmosphere, it suffers from selective absorption in molecules of the gases composing the air.

2. The Atmosphere

The atmosphere of Earth is a composition of gases surrounding the planet Earth that is retained by Earth's gravity. The atmosphere is divided into several principal layers as shown in Table 2. Pressure and density decrease in the atmosphere as height increases, while temperature may remain relatively constant or even increase with altitude in some regions.

Table 2: The layers of the atmosphere

70,000Km	Outer space				Magnetosphere
10,000Km				Plasmasphere	
800Km	Atmosphere	Exosphere	Ionosphere		
500Km		Thermosphere			
80Km		Mesosphere			
50Km		Stratosphere			
8-18Km		Troposphere			

The lower layer of the atmosphere is the Troposphere beginning at the surface and extends to between 8Km at the poles and 18 km at the equator, with some variation due to weather. The troposphere is mostly heated by transfer of energy from the surface, resulting in descending temperature with altitude. The tropospheric air is a mixture of gasses containing roughly 80% of the mass of the atmosphere. Dry air contains 78.084% Nitrogen (N_2), 20.948% Oxygen (O_2), 0.934% Argon (Ar), 0.0314% Carbon dioxide (CO_2), and small amounts of other gases. Humid atmosphere also contains a variable amount of water vapor, around 1-4%. The air also contains of dust, haze and other pollutant particles.

3. Millimeter wave propagation in the Troposphere

At lower frequencies, up to the UHF regime, the atmosphere transparent to the electromagnetic radiation propagating in the medium. However, as the frequency is increased, absorption is revealed. When millimeter-wave radiation passes through the atmosphere, it suffers from selective molecular absorption due to molecular rotational resonances mainly in water and oxygen.
The time dependent field $E(t)$ represents an electromagnetic wave propagating in a medium. The Fourier transform of the field is:

$$\mathbf{E}(f)=\int_{-\infty}^{+\infty}E(t)\cdot e^{-j2\pi ft}dt$$

In the far field, transmission of a wave, radiated from a localized (point) isotropic source and propagating in a medium is characterized in the frequency domain by the approximate transfer function:

$$H(jf)=\frac{\mathbf{E}_{out}(jf,d)}{\mathbf{E}_{in}(jf)}\propto\frac{1}{d}\cdot e^{-j\int_0^d k(f)dz}$$

Here, $k(f)=2\pi f\sqrt{\mu\varepsilon}$ is a frequency dependent propagation factor, where ε and μ are the local permittvity and the permeability of the medium, respectively. The transfer function $H(jf,d)$ describes the frequency response of the medium. In a dielectric medium the permeability is equal to that of the vacuum $\mu=\mu_0$ and the permittivity is given by $\varepsilon(f)=\varepsilon_r(f)\cdot\varepsilon_0$. If the medium introduces losses and dispersion, the relative dielectric constant $\varepsilon_r(f)$ is a complex, frequency dependent function. The resulting local index of refraction can be presented by:

$$n(f)=\sqrt{\varepsilon_r(f)}=1+N(f)\cdot 10^{-6}$$

Where the complex refractivity given in ppm is:

$$N(f)=N_0+N'(f)-jN''(f)$$

The term in the refractivity that is constant in frequencies is given by a real quantity N_0. The frequency dependent term of the refractivity is a complex function consisting of a real $N'(f)$ and imaginary $N''(f)$ quantities. The propagation factor can be written in terms of the index of refraction:

$$k(f)=\frac{2\pi f}{c}\cdot n(f)=\underbrace{-j\frac{2\pi f}{c}\cdot N''(f)\cdot 10^{-6}}_{\alpha(f)}+\underbrace{\frac{2\pi f}{c}\cdot\left(1+N_0\cdot 10^{-6}\right)+\frac{2\pi f}{c}\cdot N'(f)\cdot 10^{-6}}_{\beta(f)}$$

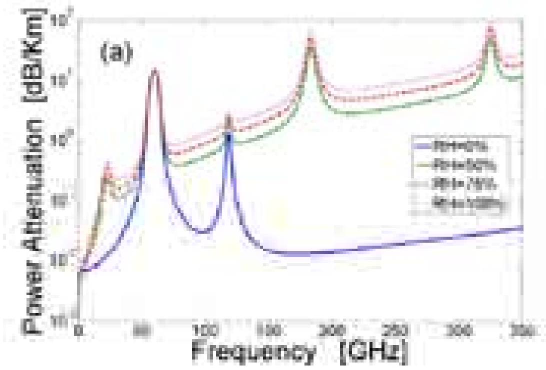
We identify the expression of the field attenuation coefficient:

$$\alpha(f)=-\operatorname{Im}\{k(f)\}=-\frac{2\pi f}{c}\cdot\operatorname{Im}\{n(f)\}=\frac{2\pi f}{c}\cdot N''(f)\cdot 10^{-6}$$

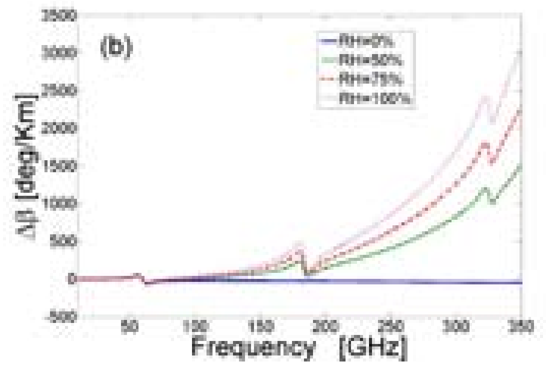
and the wavenumber:

$$\beta(f)=\operatorname{Re}\{k(f)\}=\frac{2\pi f}{c}\cdot\operatorname{Re}\{n(f)\}=\frac{2\pi f}{c}\cdot\left(1+N_0\cdot 10^{-6}\right)+\underbrace{\frac{2\pi f}{c}\cdot N'(f)\cdot 10^{-6}}_{\Delta\beta(f)}$$

The transmission characteristics of the atmosphere at the EHF band, as shown in Figure 1, was calculated with the millimeter



(a)



(b)

propagation model (MPM), developed by Liebe[1]. Curves are drawn for several values of relative-humidity (RH), assuming clear sky and no rain. Inspection of Figure 1.a reveals absorption peaks at 22GHz and 183GHz, where resonance absorption of water (H_2O) occurs, as well as absorption peaks at 60GHz and 119GHz, due to absorption resonances of oxygen (O_2). Between

1 H. J. Liebe: "MPM – An atmospheric millimeter-wave propagation model", Int. J. of Infrared and Millimeter waves 10, (6), (1989), 631-650

these frequencies, minimum attenuation is obtained at 35GHz (Ka-band), 94GHz (W-band), 130GHz and 220GHz, which are known as atmospheric transmission 'windows'.

Figure 1: Millimeter wave a) attenuation coefficient $20\log(e)\cdot\alpha(f)$ in [dB/Km] and b) $\Delta\beta(f)=\frac{2\pi f}{c}\cdot N'(f)\cdot 10^{-6}$ in [deg/Km] for various values of relative humidity (RH) at sea level.

The transmission characteristics are determined by weather conditions such as temperature, pressure and humidity. The absorption is proportional to air density, and thus reduces with height. Attenuation due to fog, haze, clouds, rain and snow is one of the dominant causes of fading in wireless communication links operating in the EHF band. Raindrops and dust scatter millimeter wave radiation, resulting in amplitude fluctuations and phase randomness in the received signal. This further degrades the availability and performance of the communication links. Sufficient fade margins are essential for a reliable system.

4. Summary

The inhomogeneous transmission in a band of frequencies causes absorptive and dispersive effects in the amplitude and in phase of wide-band signals transmitted in the EHF band. The frequency response of the atmosphere plays a significant role as the data rate of a wireless digital radio channel is increased. The resulting amplitude and phase distortion leads to inter-symbol interference, and thus to an increase in the bit error rate (BER). These effects should be taken into account in the design of broadband communication systems, including careful consideration of appropriate modulation, equalization and multiplexing techniques.

Prof. Yosef Pinhasi

Yosef Pinhasi is the Dean of the Faculty of Engineering at the Ariel University of Samaria. He was born in Israel on May 3, 1961, received the B.Sc., M.Sc. and Ph.D. degrees in electrical engineering from Tel-Aviv University, Israel in 1983, 1989 and 1995 respectively. He served as the head of the Department of Electrical and Electronic Engineering between the years 2004-2007.

Since 1990 he is working in the field of electromagnetic radiation, investigating mechanisms of its excitation and generation in high power radiation sources like microwave and millimeter wave electron devices, free-electron lasers (FELs) and masers. He developed a unified coupled-mode theory of electromagnetic field excitation and propagation in the frequency domain, enabling study of wideband interactions of electromagnetic waves in media in the linear and non-linear (saturation) operation regimes.

Prof. Pinhasi investigates utilization of electromagnetic waves in a wide range of frequencies for various applications such as communications, remote sensing and imaging. The space-frequency approach, which developed by him, is employed to study propagation of wide-band signals in absorptive and dispersive media in broadband communication links, and wireless indoor and outdoor networks as well as in remote sensing Radars operating in the millimeter and Tera-Hertz regimes.

Prof. Yosef Pinhasi is the Chairman of the Communication and Information Technology Chapter, of the Society of Electrical and Electronic Engineers, Member of the executive board of the Israeli Association of the Plasma Science and Applications serving as its secretary, Chairman of Technical Standardization Expert Committee of Communication in smart Grid, The Standards Institution of Israel (SII).